On the Use of Stable Isotopes To Trace the Origins of Ice in a Floating Ice Tongue[1]

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Stable isotope analysis has been used successfully to distinguish between several different ice types in an ice tongue floating on sea water in Antarctica. At one critical location this technique has provided the only means of discriminating unambiguously between glacial ice and fresh-water ice formed from desalinated sea water. This part of the ice tongue is now underlain by a layer of desalted sea water thick enough to prevent any further accretion of sea ice at this location.

The floating shelflike tongue of the Koettlitz glacier, which extends for a distance of approximately 50 km into McMurdo Sound, Antarctica (Figure 1), has attracted considerable scientific attention mainly because of the fish and other marine animals found on its ablating surface [*Debenham*, 1920, 1948, 1965; *Swithinbank et al.*, 1961; *Swithinbank*, 1970; *Gow et al.*, 1965; *Gow*, 1967]. *Debenham* [1920] hypothesized that these remains were originally incorporated into the bottom of the ice tongue by the freezing-on of sea water and were then subsequently exposed by ablation (melting) of the upper surface of the ice tongue.

The first test of Debenham's hypothesis was conducted by *Gow et al.* [1965], who discovered by core drilling that the ice tongue in the vicinity of the Dailey Islands (located near the ice front) was composed of fresh-water ice not sea ice, as was required by the hypothesis. Subsequently, however, it was discovered by *Zotikov and Gow* [1967] that the ice immediately upstream of the Dailey Islands was saline. Additional drilling by *Gow* [1967] along the center line of the ice tongue showed that it was indeed composed of sea ice for a distance of 26 km back from the ice front. The thickness of ice varied from 9 to 15 meters, and the actual transformation from a glacial ice tongue to a sea ice shelf could be observed at a number of locations. The results of this exploratory drilling not only confirmed Debenham's long-standing hypothesis of sea ice replacement of the Koettlitz glacier but also disposed of any possibility that the fresh-water ice near the Dailey Islands was glacial in origin. The exact nature of this fresh-water ice was not resolved until core samples were subjected to stable isotope analysis. These data are considered sufficiently interesting to be published independently of the other studies conducted on the Koettlitz ice tongue. They not only resolve a very interesting glaciological anomaly but with data obtained at other locations serve to demonstrate the great value of isotopic methods in tracing the origins of the ice in a composite glacier such as the Koettlitz. The same technique has since been applied by *Lyons et al.* [1971] to help resolve the internal structure of an arctic ice shelf.

ANALYTICAL TECHNIQUES

The isotopic composition of sea water is relatively constant throughout the oceans of the world, and only minor fractionation of the stable isotopes occurs when sea water freezes. According to *Friedman et al.* [1964], sea ice

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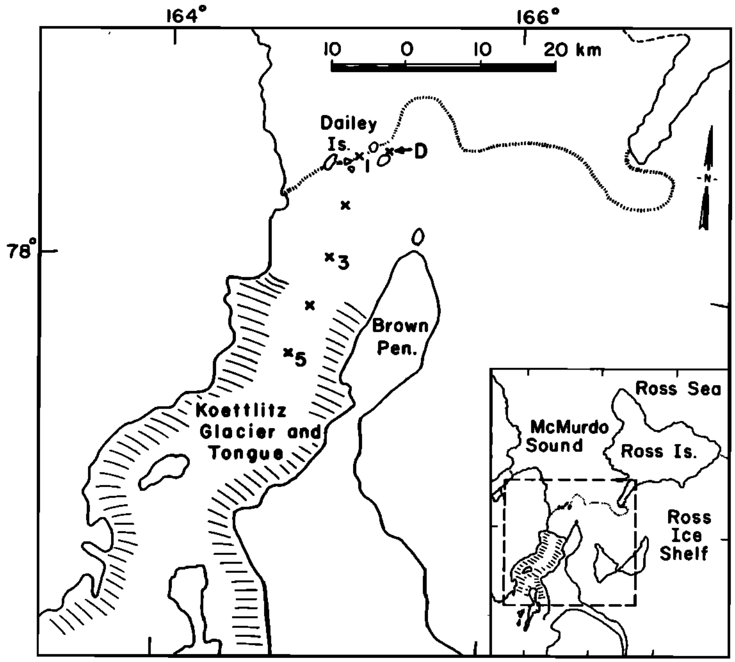

Fig. 1. Map of McMurdo Sound region showing locations of drill holes on the Koettlitz glacier tongue. Data in this report are restricted to measurements made on cores from holes 1, 3, and 5 and from the hole marked D, drilled directly in front of the easternmost Dailey Island.

contains only about 2% more deuterium than the water from which it was frozen, and a parallel fractionation can be expected for ^{18}O. The sea water to sea ice fractionation is very minor in comparison with fractionation processes in the atmosphere, which ultimately lead to the precipitation in the polar regions of snow very much depleted in deuterium and ^{18}O. The principles involved in the fractionation of oxygen isotopes are discussed by *Epstein and Mayeda* [1953], *Dansgaard* [1953], and *Epstein* [1956]. Essentially, the same relationships apply to the fractionation of the hydrogen isotopes [*Friedman et al.*, 1964]. Isotope variations are expressed here as a deviation δ from standard mean ocean water (SMOW), a positive value indicating enrichment and a negative value indicating depletion with respect to SMOW.

Isotopic data were supplemented by measurements of electrolytic conductivity of melted core samples. These data were then converted to salinities on the assumption that the ratios of salts in the ice samples were the same as those in standard sea water.

RESULTS AND DISCUSSION

Results of isotopic and salinity measurements of samples from the Koettlitz ice tongue are presented in Tables 1 and 2. Core holes 1 and 3 (see Figure 1 for the locations of drill holes) were drilled in ice provisionally identified as sea ice on the basis of salinity and petrographic studies of the cores. Results of studies at hole 1 are presented by *Zotikov and Gow* [1967], and identical relationships were subsequently observed in cores from hole 3. Ice from core hole 5 was provisionally identified as glacial ice, which in terms of texture (Figure 2) and salt content differs radically from sea ice. Stable isotope data in Table 1 confirm these identifications completely.

The δ values at the locations of holes 1 and 3 show little if any significant variation with depth in the ice, but they all show a slight positive deviation or enrichment in deuterium and ^{18}O. The only exception is the sample of sea water obtained from the bottom of hole 3. This water was enriched slightly in salt (41‰ as compared with 33‰ for sea water in McMurdo Sound), probably as a result of rejection of

TABLE 1. Stable Isotope and Salinity Variations of the Koettlitz Glacier Tongue, McMurdo Sound, Antarctica

Sample Location	Sample Depth, meters	δD, °/oo	$\delta^{18}O$, °/oo	Salinity, °/oo	Ice Type
Hole 1	0.1	+18.3	+2.51	0.2	Sea
	1	+11.8	+1.57	1.00	Sea
	4	+15.2	+1.67	1.44	Sea
	8	+16.1	+1.80	2.39	Sea
	11	+12.9	+1.51	3.13	Sea
	12	+14.6	+1.37	3.19	Sea
	12.8	+15.4	+1.61	3.76	Sea
Hole 3	2	+14.4	+1.76	2.10	Sea
	6	+13.8	+1.74	3.26	Sea
	9	+15.2	+1.90	1.75	Sea
	11	+13.6	+1.66	3.82	Sea
	12	+12.8	+1.77	2.88	Sea
	12.9	+15.1	+1.83	3.51	Sea
	13	+13.7	+1.85	5.26	Sea
	*	-05.6	-1.12	41.0	Sea
Hole 5†	1	-288.8	-38.17	0.05	Glacial
	7	-257.3	-33.46	0.01	Glacial

For locations of samples see Figure 1.
*Sea water from bottom.
†Did not penetrate to bottom of ice tongue at this location; other two holes penetrated ice bottom.

salts during freezing, and the deuterium value is very close to that reported for antarctic deep water [*Friedman et al.*, 1964]. The approximate 2% enrichment in deuterium of the sea ice over that of the sea water also agrees very closely with the theoretical and observed values reported by *Friedman et al.* [1964] and with the values reported by *O'Neil* [1968] for fractionation between ice and fresh water.

TABLE 2. Stable Isotope Variations in Ice from the Vicinity of the Dailey Islands, Koettlitz Glacier Tongue, McMurdo Sound, Antarctica

Sample Depth, meters	δD, °/oo	$\delta^{18}O$, °/oo	Ice Type*
4	-7.3	-0.34	FW
6	-6.5	-0.48	FW
7	+0.4	-0.58	FW
7.7	-4.3	-0.62	FW
†	-21.1	-3.16	UFW

Location D in Figure 1.
*FW, fresh-water ice derived from the melt water of desalinated sea ice; UFW, unfrozen fresh water.
†Sub-ice water sample.

It had been suggested by *Zotikov and Gow* [1967] on the basis of temperature measurements in a drill hole that brackish water, formed from the mixing of sea water and glacial melt, might be involved in the freezing process. This possibility was heightened by the knowledge of the existence of a body of fresh water located directly beneath the ice in the vicinity of the Dailey Islands [*Gow et al.*, 1965]. However, the δ values at core holes 1 and 3 clearly show that only straight sea water is freezing onto the bottom of the ice tongue at these two locations. This freezing has produced exceptional thicknesses of sea ice. At hole 4, for example, the ice measured nearly 15 meters thick. This thick-

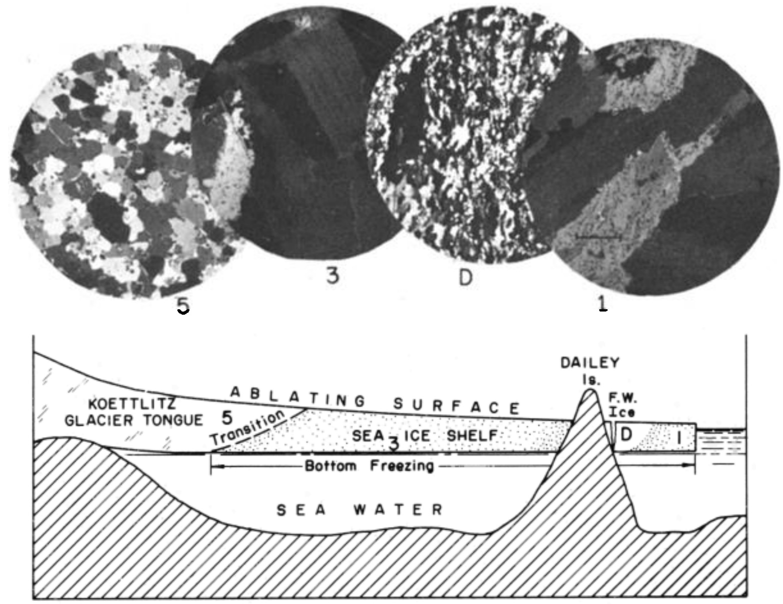

Fig. 2. Schematic cross section of Koettlitz glacier tongue depicting (top) crystal structure characteristics of the major ice types and (bottom) processes involved in its formation. The scale bar on the section of sea ice from hole 1 measures 1 cm. This same scale also applies to the other three sections. Glacier ice from hole 5 is composed of equidimensional crystals and contains numerous bubbles of air. Sea ice from holes 1 and 3 features elongated interlocked crystals. Parallel trains of inclusions are brine pockets. Very fine grained crystal structure of ice from near the tide crack at D is typical of fresh-water (F.W.) frazil.

ness is for actively growing sea ice and certainly exceeds the 12-meter maximum thicknesses of sea ice reported from the Arctic by *Cherepanov* [1966].

Salinities of cores from hole 5 are less than those at locations 1 and 3 by 2–3 orders of magnitude, and the isotopic composition of ice at location 5 clearly demonstrates that it is of glacial origin. The very low concentrations of deuterium and ^{18}O would indicate that this ice originated in the upper reaches of the Koettlitz glacier. On the basis of present day relationships between isotopic composition and temperature [*Lorius*, 1968] and temperature and elevation [*Bentley et al.*, 1964] the ice at location 5 probably formed in a region of mean annual air temperature of $-28°$ to $-30°C$ at an elevation of about 1000 meters on the Koettlitz glacier. This location would be approximately 40 km upstream from hole 5. The deuterium concentrations at hole 5 are very similar to those measured by *Ragotzkie and Friedman* [1965] in Lake Vanda, situated in the Wright Valley, Victoria Land, Antarctica. Wright Valley is located about 90 km to the northwest of hole 5 on the Koettlitz ice tongue, and the low deuterium concentrations in Lake Vanda are attributed by *Ragotzkie and Friedman* [1965] to the inflow of melt water from the Upper Wright and Lower Wright glaciers. Together these two glaciers span much the same range of elevations as the Koettlitz glacier, but only the Lower Wright glacier is contributing melt water ($\delta D = -259‰$) at the present time.

The most interesting data were obtained in the vicinity of the Dailey Islands, where the first of two holes drilled in November 1963 [*Gow et al.*, 1965] showed that this part of the Koettlitz ice tongue was actually composed of salt-free ice. It was also discovered that the ice was underlain by a body of fresh water, the existence of which was attributed to the drainage down tide cracks of surface melt water formed during the ablation season. Tide cracks are formed as a result of the rise and fall of the ice in contact with the islands. During the summer, considerable quantities of water are discharged into those cracks, and freezing of this water to the underside of the ice tongue was believed to be a major source of nourishment at this location. *Friedman et al.* [1961] have reported a similar situation involving the freezing of surface snow melt to the underside of arctic sea ice. However the ultimate source of the fresh water at the Dailey Islands (whether derived from glaciers or from seasonal snow melt) could not be determined for certain. Ice from a second hole, located approximately 400 meters from the first, was tentatively identified as glacial ice on the basis of petrographic studies [*Gow et al.*, 1965]. The isotope data (Table 2) disprove both the glacial and snow melt origins. Instead, it would appear that both the ice and the underlying melt water are of direct marine origin. Though salt concentrations in this ice varied from 15 to 90 ppm [*Gow et al.*, 1965], very much less than the variation in sea ice and actually approaching polar glacial ice in purity, δ values of both the ice and the underlying fresh water approximate closely the isotopic composition of antarctic sea water.

The simplest explanation of the above observations is that the ice in the vicinity of the Dailey Islands was originally as saline as that in other parts of the ice tongue but that at some stage in the history of ice growth the sea water per se was replaced by desalted sea water. Desalination is a characteristic phenomenon of aging sea ice, a fact that is clearly indicated in the salinity data obtained on samples at holes 1 and 3. At both locations the near-surface (or older) sea ice is appreciably depleted in salts. Fresh-water melt pools and streams occur over much of the surface of the Koettlitz ice tongue, but it is only in the vicinity of the Dailey Islands, where tide cracks penetrate to the bottom of the ice tongue [*Gow et al.*, 1965], that surface melt water is able to drain down to the underside of the ice. Here it becomes sandwiched between the ice bottom and the slightly denser sea water, which it now replaces in the accreting process. This body of fresh water is estimated to be at least 3 meters thick at hole 1. When this water freezes, it does so with all the petrographic and salinity characteristics of fresh-water ice; yet, it still retains the isotopic identity of sea water. Measurements of surface ablation and ice thickness at this location indicate that it would take 15–20 years for bottom ice to reach the surface.

In a sense, this system is a self-generating one apparently with little or no interaction with other sources of water. This circumstance could explain why the δ values of the water and the overlying ice are practically the same, though other factors concerned with freezing may be involved. For example, observations by *Gow et al.* [1965] indicate that freezing could be occurring at the interface between the sea water and the fresh water rather than the water's being frozen directly to the underside of the ice. Crystals formed at the interface would then float up and attach themselves to the undersurface of the ice. Such a process has been advocated by *Untersteiner and Badgley* [1958] to explain the freezing of fresh water to the undersides of ice floes in the Arctic Ocean. The operation of a similar mechanism in the vicinity of the Dailey Islands would also be compatible with the frazillike textures that characterize the ice at this location, as is illustrated in Figure 2. Whatever the mechanism of ice accretion might be at this location, it would appear that an essentially nonfractionating process of freezing is occurring in the fresh-water layer. The inferred compositional structure of the Koettlitz ice tongue is demonstrated schematically in Figure 2.

CONCLUSIONS

Stable isotope studies definitely confirm the fact that the lower half of the 50-km-long Koettlitz ice tongue, McMurdo Sound, Antarctica, is composed of sea ice up to 15 meters thick. This transformation is accomplished by the combined processes of ablation of the original glacial ice at the upper surface and freezing of sea water onto the bottom. Straight sea water only appears to have been involved in the freezing process. No evidence was obtained for brackish-water ice, not even in the anomalous region of salt-free ice near the Dailey Islands, where the ice tongue is underlain directly by fresh water. This fresh water is shown by stable isotope analysis to be of direct marine origin and is derived most probably from the melting of old desalinated sea ice on the upper surface of the ice tongue. This water drains down tide cracks to the underside of the ice, where it forms a stable body of fresh water, which naturally gives rise to salt-free ice when it freezes. It would appear that enough fresh water is produced during the ablation season to sustain the fresh-water layer and thus prevent any further accretion of sea ice at this location. The formation of fresh-water (nonglacial) ice in this way is almost certainly limited to areas within the immediate vicinity of tide cracks.

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